

# Natural Gas Transportation Technology Pathways to Achieve Air Quality Goals

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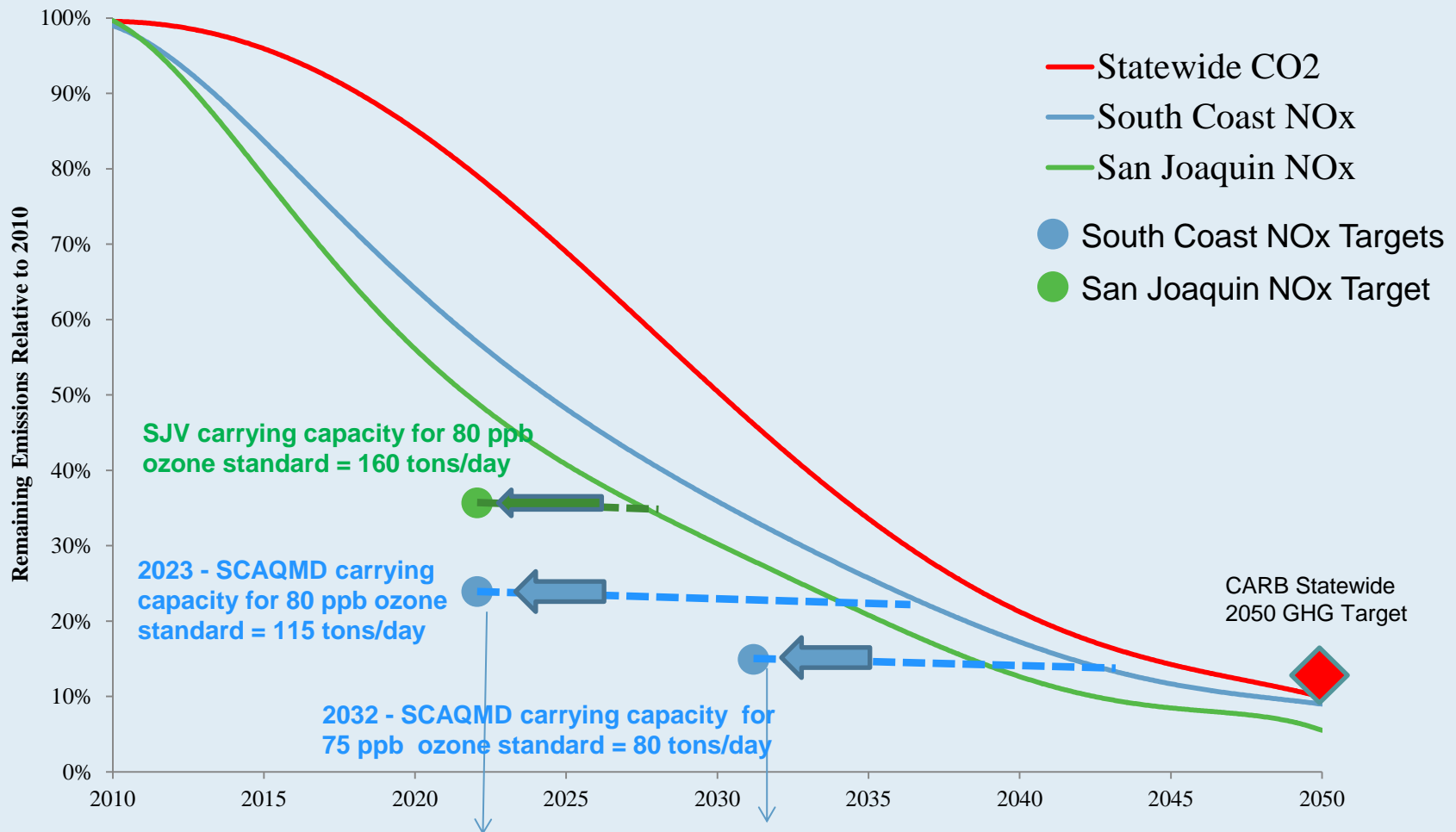
October 16, 2014

# Southern California Gas Company

- » Subsidiary of Sempra Energy (SRE)
- » The nation's largest natural gas distribution utility
  - 20.9 million consumers
  - 5.8 million meters
  - 500 communities
  - Annual Throughput 1TCF
  - 4 Storage Fields 136 BCF
- » Industry leader in customer satisfaction, safety and cost-effectiveness



# Current Paths Miss Emissions Goals



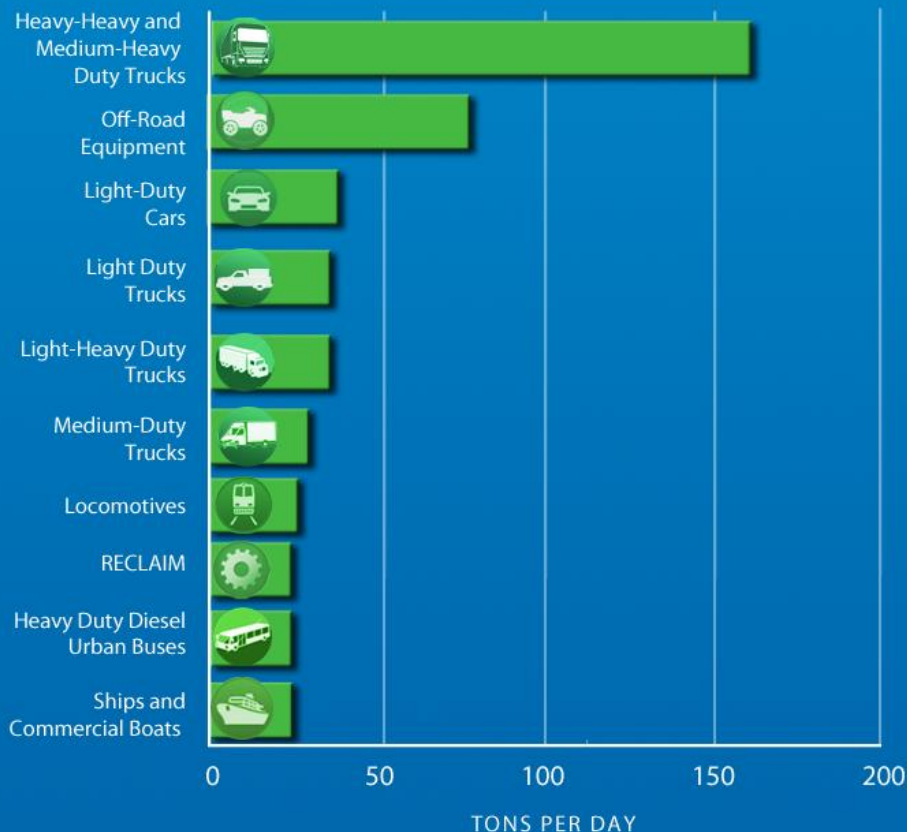
Source:

Curves based on CARB Vision for clean air Scenario 3 in CARB vision model, available at <http://www.arb.ca.gov/planning/vision/vision.htm>

# Natural Gas Transportation Pathways For Today

## Top 10 NOx Source Categories

SCAQMD NOx



Note: Based on the 2012 NOx inventory from the California Air Resource Board(CARB)  
Source: CARB Stfap Report for 8-Hour Ozone State Implementation Plan Emission Inventory Submittal



- Heavy Duty Trucks
- Buses
- Rail
- Marine
- Cargo Handling
- Construction

# Natural Gas: A Foundational Fuel

- ✓ Abundant
- ✓ Affordable
- ✓ Domestic
- ✓ Clean



# Offering Cleaner Solutions for The Mobile Sectors

← **Current Focus** →

← **Expanding Focus** →



**Fleet Vehicles**



**Heavy Duty Trucks**



**Cargo Handling  
Equipment**



**Locomotives**



**Marine Vessels**



**CNG**

A  Sempra Energy utility®



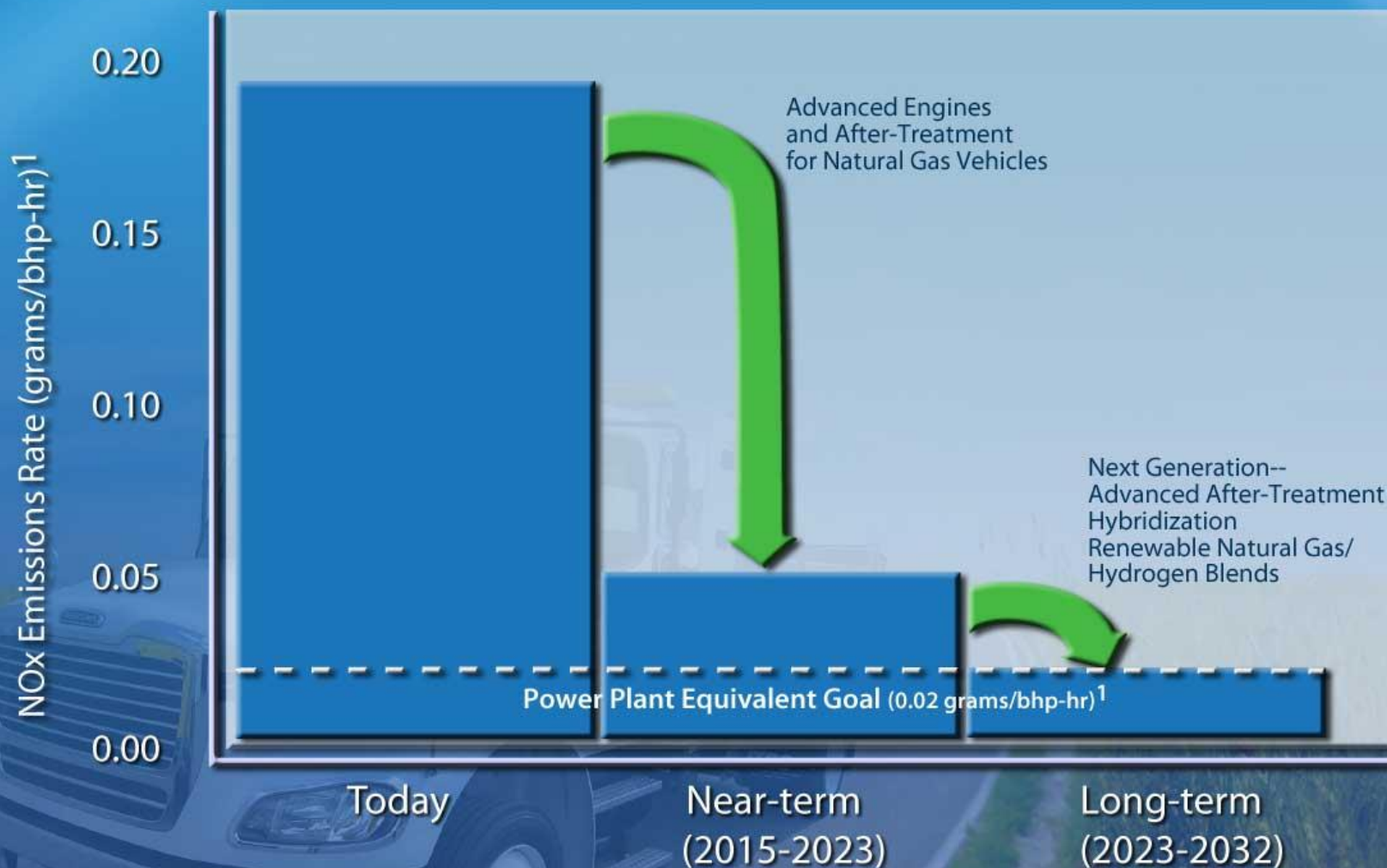
**LNG**

*Glad to be of service.®*

# “Near Zero” NOx Emissions for Heavy Duty Truck is Achievable through Technology Development



A Sempra Energy utility\*



<sup>1</sup>. grams per brake horsepower hour (g/bhp-hr)

# Applying the Five Strategies for NOx Reductions from Natural Gas HDVs

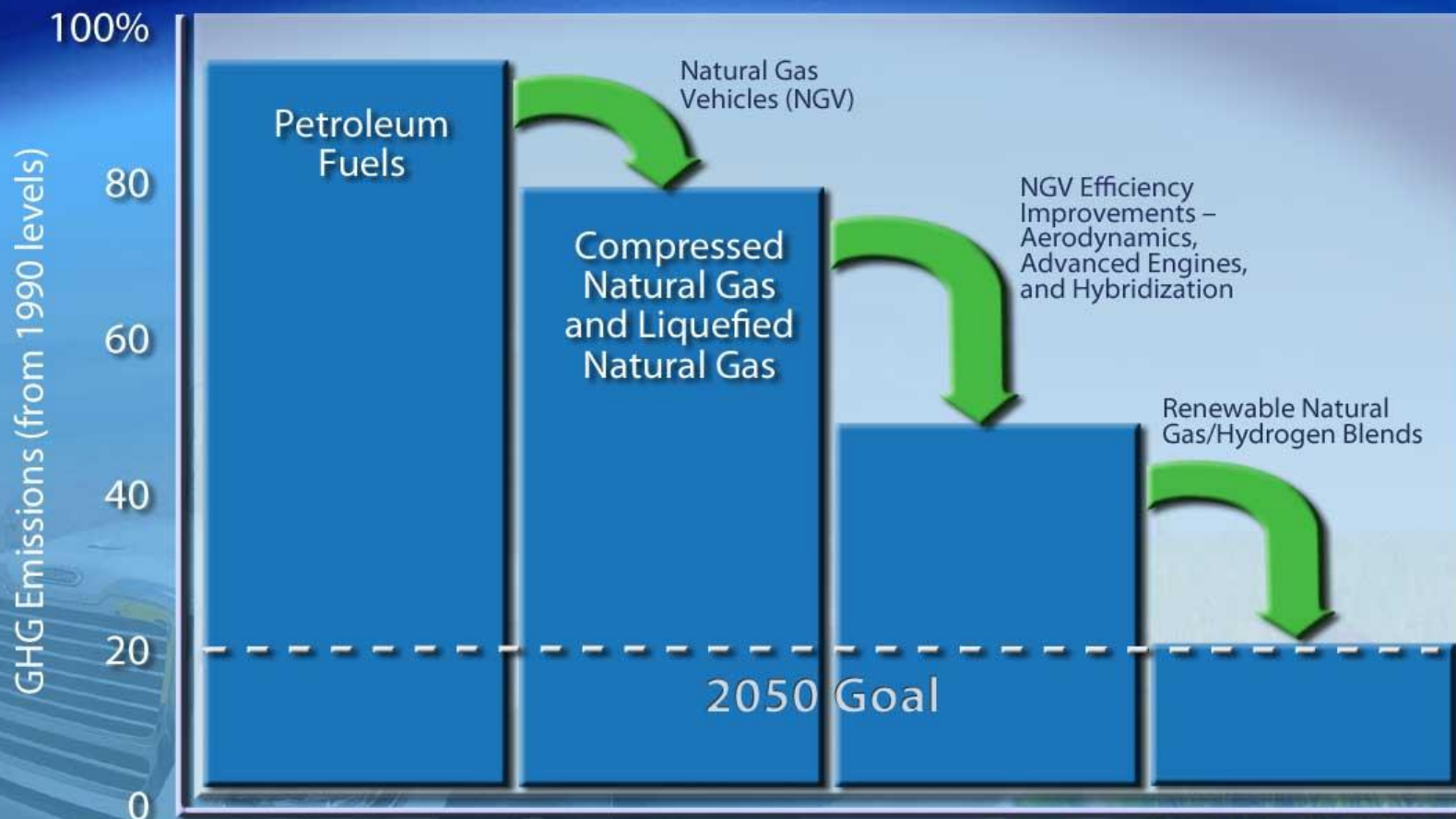
	Today	Near-term (2013-2023)		Long-term (2023-2032+)
Targets	<0.2g NOx	<0.05g NOx	<0.02g NOx	ZE Miles, Net Zero, ZE Equivalent
Strategies / Technologies	Dedicated NG engines	Advanced Engines (improved combustion and engine efficiency reduce emissions)		
		Hydrogen/methane blends, Improved ultra lean ignition & air/fuel control technologies (Reduces fuel pathway NOx emissions)		
	Three-way catalysts, SCR	Advanced After-treatment (Westport committed)	Hybrids: Battery-electric, Hydraulic	Hybrids: Catenary, Plug-in, Fuel Cell CNG/H2 Blends
	Aerodynamics, Weight Reduction, and Rolling Resistance Reduction Strategies (reduces vehicle energy needs and related fuel consumption)			

# Technologies Also Address Greenhouse Gas (GHG) Goals

Efficiency Improvements & Renewables Availability Increase Over Time



A Semptra Energy utility



# Down selected engine and vehicle technology descriptions (1/3) – Air System, Combustion and Fuel System

## Technology Description – (1/3)

System	Technology	Description
Air System	Miller Cycle	<ul style="list-style-type: none"> <li>Miller cycle for natural gas engines involves increased boosting coupled with early or late closure of intake valves during intake and compression strokes, which results in longer effective expansion ratios than compression ratios and hence reduces compression work (Compression work is partly transferred to the turbocharger) on fuel air mixture and leads to greater degree of fuel air mixture cooling, yielding lower temperatures at end of compression, enabling both lower NOx emissions (Due to lower charge temperatures) and fuel consumption (Due to potential for spark timing advance w/o knock)</li> </ul>
	Atkinson Cycle	<ul style="list-style-type: none"> <li>Atkinson cycle for gas engines also involves longer effective expansion ratios than compression ratios by early/late intake valve closure or through slider mechanism in crank train</li> </ul>
	Camless Engine	<ul style="list-style-type: none"> <li>Camless technology employs electro mechanical or hydraulic actuator that does away with camshafts and associated components and offers greater flexibility of intake, exhaust valve timings, durations, opening/closing profiles etc., thus offering addl. control variables to enable low NOx, CO<sub>2</sub> combustion</li> </ul>
Combustion	Lean Burn	<ul style="list-style-type: none"> <li>Combustion of fuel in a mixture with excess amount of air (Anywhere from to ~40% - 100% more) than what is necessary to completely combust fuel into CO<sub>2</sub> and water vapor, resulting in lower combustion temperatures and reduced NOx formation</li> </ul>
	HCCI (Homogenous Charge Compression Ignition)	<ul style="list-style-type: none"> <li>HCCI with natural gas refers to compression ignition (At high compression ratios) of a homogenous (highly premixed charge attained via port gas injection or very early in cylinder gas injection) natural gas and air mixture, which offers the potential to achieve ultra low in cylinder NOx and PM emissions and potentially reduced fuel consumption (CO<sub>2</sub> emissions) if the rapid heat release due to combustion is controlled and occurs near the thermodynamically efficient location of top dead center</li> </ul>
	Pre-Chamber Spark Ignited	<ul style="list-style-type: none"> <li>Pre-chamber natural gas engines have a smaller volume, pre combustion chamber with a spark plug, within the main cylinder and this confined volume leads to charge stratification, with a rich mixture within the pre-chamber igniting first, which then enables ignition of overall very leaner mixtures within the rest of the cylinder, which results in lower combustion temperatures and reduced NOx emissions</li> </ul>
	Stratified Charge	<ul style="list-style-type: none"> <li>Stratification is an enabler of lean burn combustion and refers to creating thermal or chemical non homogeneity in the fuel air mixture within cylinder, both temporally and spatially and this can be done in many ways, e.g. by employing a pre-chamber or by direct injection of a 2<sup>nd</sup> pilot ignition fuel like in a HPDI gas engine or via induced turbulence etc., all of which aids in ignition of a variety of natural gas mixtures, incl. lean mixtures, leading to potential NOx and fuel consumption benefits</li> </ul>

# Down selected engine and vehicle technology descriptions (2/3) – Waste Heat Recovery and Emissions Treatment

## Technology Description – (2/3)

System	Technology	Description
Fuel System	Increased Fuel Injection Pressure	<ul style="list-style-type: none"> <li>Higher fuel injection pressures are associated with in cylinder injection systems used for main injection of gas and pilot injection of diesel in HPDI gas engines that enable better atomization and associated better mixing of fuel air mixture and also enables further optimization of main and pilot fuel injection events and overall engine calibration for favorable NOx, fuel consumption trade off</li> </ul>
	Rankine Cycle	<ul style="list-style-type: none"> <li>Thermodynamic cycle that recovers heat from engine exhaust and other heat exchangers (e.g. EGR coolers) by using a refrigerant fluid like R245fa that absorbs waste heat and is then expanded in a downstream turbine, thus producing additional useful power and lowering overall CO<sub>2</sub> emissions</li> </ul>
Waste Heat Recovery	Thermo-Chemical Recuperation	<ul style="list-style-type: none"> <li>TCR refers to a means to recover heat from engine exhaust and other heat exchangers (e.g. EGR coolers) by using the heat to reform a hydrocarbon fuel typically into syngas (mixture of CO and H<sub>2</sub>) with higher calorific energy content and combusting this syngas in the cylinder, which then permits ignition of leaner mixtures due to the H<sub>2</sub> content in the syngas, thus enabling lower NOx emissions</li> </ul>
	Steam/Water Injection	<ul style="list-style-type: none"> <li>Involves injecting steam or water directly in cylinder or upstream in the port or manifold, which results in lowering the charge temperature, thus resulting in lower end of compression temperatures and hence lower NOx emissions and also potentially permits spark timing advance, leading to lower CO<sub>2</sub> emissions</li> </ul>
Emissions Treatment	Exhaust Gas Recirculation	<ul style="list-style-type: none"> <li>Involves recirculating portion of combusted gases from previous cycle to mix with fresh fuel air charge, which increases specific heat of new in cylinder charge, leading to lower combustion temp. and results in lower NOx emissions and potentially permits spark timing advance, leading to lower CO<sub>2</sub> emissions</li> </ul>
	Selective Catalytic Reduction	<ul style="list-style-type: none"> <li>SCR is an emissions aftertreatment solution typically employed on lean burn natural gas engines today to reduce NOx emissions and involves injecting a reductant like Urea (typically diluted in two thirds water) into the exhaust stream after the turbocharger, which mixes with the exhaust and reduces engine out NOx into N<sub>2</sub> and water over a catalyst (e.g. catalysts like Vanadia, Cu-Zeolite)</li> </ul>
	Non Selective Catalytic Reduction	<ul style="list-style-type: none"> <li>NSCR (Pt, Pd based 3 way cat.) is an emissions aftertreatment solution typically employed after the turbocharger on stoichiometric (rich burn) natural gas engines today to reduce NOx, CO, HC emissions</li> </ul>
	Lean NOx Trap	<ul style="list-style-type: none"> <li>LNT or NOx adsorbers is an emissions aftertreatment solution typically employed after the turbocharger on lean burn natural gas engines to reduce NOx emissions by adsorbing NOx onto an adsorbent during lean operations and reducing it to N<sub>2</sub> over a reduction catalyst during rich operations (Can be attained by injecting fuel into exhaust or via in cylinder injection strategies)</li> </ul>

# Down selected engine and vehicle technology descriptions (3/3) – Ignition System, Design, Vehicle System and Powertrain

## Technology Description – (3/3)

System	Technology	Description
Ignition System	Improved Ignition	<ul style="list-style-type: none"> <li>Technologies that enable precise control of spark ignition timing, duration, energy discharge rates, number of spark events etc., all of which then enables ignition of a wide variety of natural gas mixtures with different ignition chemistries and kinetics (Lean, high EGR, varying gas quality mixtures)</li> </ul>
Design	Increased Firing Pr. And Peak Cyl. Pr.	<ul style="list-style-type: none"> <li>Increasing engine firing pressure and peak cylinder pressure capability is a potential enabler for HCCI, overall engine downsizing, higher part load efficiencies and operation at higher BMEP's, which enables both lower NOx and fuel consumption (CO<sub>2</sub> emissions) and this requires appropriate material selection (e.g. CGI) for the engine structure, in particular the head and block</li> </ul>
Friction & Parasitics	Reduced accessory load	<ul style="list-style-type: none"> <li>Involves reduction of engine accessory parasitic loads from the fuel system, cooling system etc. through the use of intelligent, engine load/operating cycle dependent parasitic power demand from the accessories, which then enables overall reduced fuel consumption (CO<sub>2</sub> emissions)</li> </ul>
	Reduced friction	<ul style="list-style-type: none"> <li>Involves use of combination of technologies like engine down-speeding, use of friction reducing lubricants with properties that ensure appropriate lube film thickness under high temperatures, pressures and exhaust gas concentrations in cylinder, coatings and intelligent lubrication systems, which then enables overall reduced fuel consumption (CO<sub>2</sub> emissions)</li> </ul>
Vehicle System	Aerodynamics	<ul style="list-style-type: none"> <li>Involves reduction of the overall coefficient of drag of the truck and trailer combination (Incl. undercarriage) through the use of advanced CFD modeling and associated wind tunnel testing, which then enables lower overall wind resistance and reduced fuel consumption (CO<sub>2</sub> emissions)</li> </ul>
	Lower Rolling Resistance	<ul style="list-style-type: none"> <li>Involves development of advanced tire technology (Tread patterns, width and depth, sidewall construction, compounds used) and associated pressure monitoring systems that reduces rolling resistance coefficients for smaller energy consumption per tire for distance travelled</li> </ul>
	Lower Weight	<ul style="list-style-type: none"> <li>Involves overall mass reduction at vehicle level by strategically using a variety of light weight materials ranging from plastics, aluminum, high strength steel, magnesium, composites etc. across body, chassis and interior of vehicle, all of which adds to lower overall vehicular mass and lower fuel consumption</li> </ul>
Powertrain	Hybridization	<ul style="list-style-type: none"> <li>Typically accomplished via hydraulic, pneumatic, flywheel or electric means and typically involves recuperation and storage of energy for short periods of time during select parts of a drive cycle and discharge of this stored energy to either replace or augment the engine power during parts of a drive cycle, thus reducing overall fuel consumption (CO<sub>2</sub> emissions)</li> </ul>

# Engine air System and combustion technology assessment for NOx and CO<sub>2</sub> reductions on natural gas engines

## Technology Capabilities Assessment – (1/4)

Before 2023

2023 - 2032

Sub System	Technology	Est. Tailpipe NOx (g/hp-hr) Reduction From Base EPA 2010		Est. Engine Level CO <sub>2</sub> Reduction	
Air System	Miller & Atkinson Cycles	10% - 30%	<ul style="list-style-type: none"> <li>Est. based on larger off highway gas engines; when coupled with 2 stage turbocharging systems, upper limits could be attained</li> </ul>	3% - 15%	<ul style="list-style-type: none"> <li>Combination of variable valve timing + lift and optimized turbocharging</li> </ul>
	Camless Engine	Up to 30% to 40 %	<ul style="list-style-type: none"> <li>Est. based on claims from efforts in R&amp;D stage and can vary based on trapped EGR and overall valve train, air system strategies</li> </ul>	5% - 20%	<ul style="list-style-type: none"> <li>Est. based on claims from efforts in the R&amp;D stage currently</li> </ul>
Combustion	HCCI	75% - 90%	<ul style="list-style-type: none"> <li>HCCI expected to be more of a NOx reduction tool</li> </ul>	5% - 25%	<ul style="list-style-type: none"> <li>Est. based on using HCCI as part of a multi mode combustion strategy, i.e. implies HCCI not used at full loads due to controls limitations</li> </ul>
	Pre-Chamber Spark Ignited (Lean burn)	20% - 25%	<ul style="list-style-type: none"> <li>Based on est. from large off highway gas engines; overall reduction could be higher when combined w/ EGR, boosting, suitable ignition systems</li> </ul>	4% - 18%	<ul style="list-style-type: none"> <li>Based on est. from large off highway gas engines and current on highway pre chamber systems being developed</li> </ul>
	Stratified Charge	20% - 70%	<ul style="list-style-type: none"> <li>Assumes using lean burn or stratified charge near the natural gas flammability limit with suitable ignition system to achieve upper ends of NOx reduction potential</li> </ul>	5% - 40%	<ul style="list-style-type: none"> <li>Benefit will depend on means adopted to achieve stratification or to lean mixture close to the natural gas flammability limit – Pre chamber, improved ignition system etc.</li> </ul>
	Lean Burn				

# Engine design, heat recovery and ignition system technology assessment for NO<sub>x</sub> and CO<sub>2</sub> reductions on natural gas engines

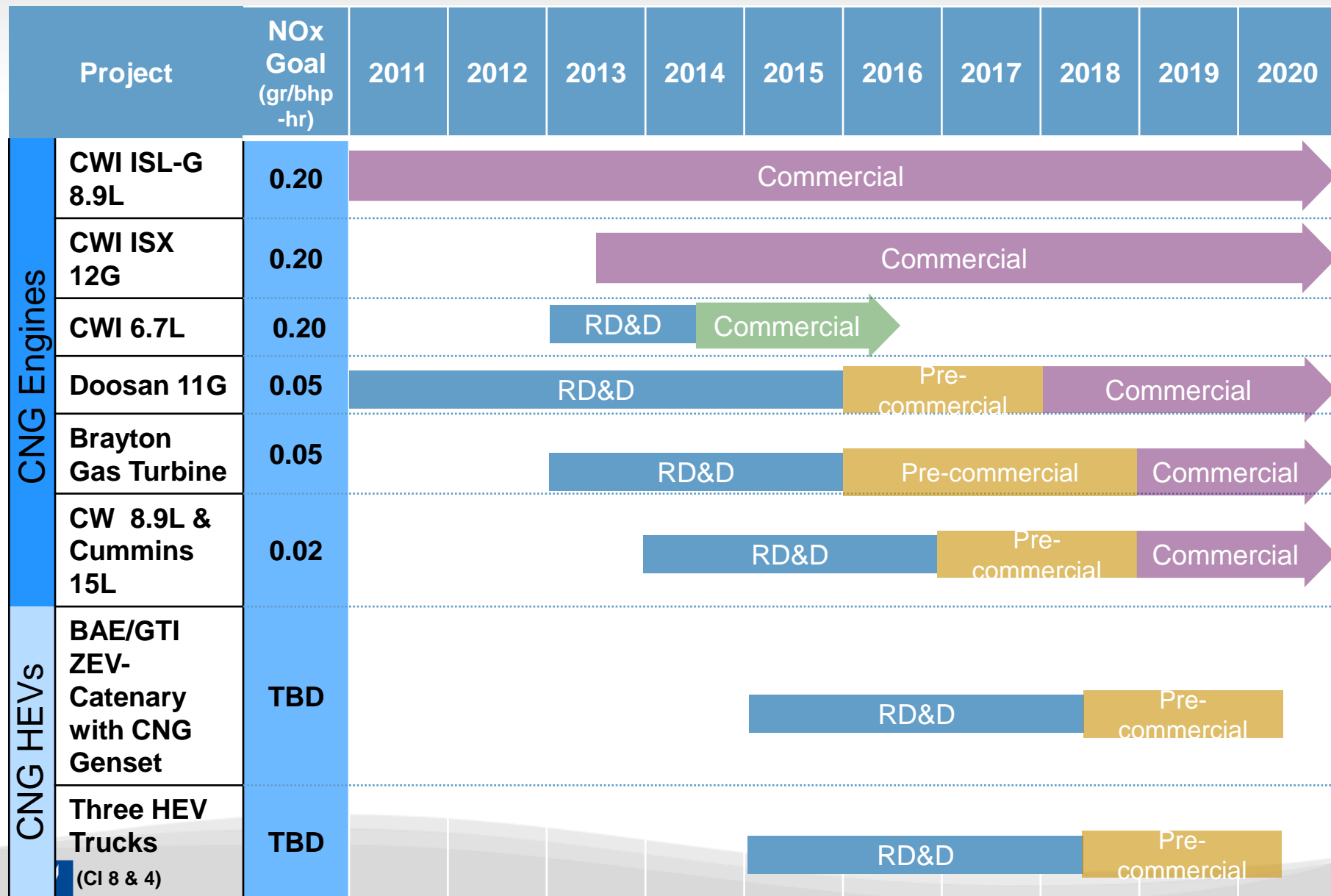
## Technology Capabilities Assessment – (2/4)

Before 2023

2023 - 2032

Sub System	Technology	Est. Tailpipe NO <sub>x</sub> (g/hp-hr) Reduction From Base EPA 2010		Est. Engine Level CO <sub>2</sub> Reduction	
Fuel System	Increased Fuel Injection Pressure (Diesel only)		<ul style="list-style-type: none"> <li>Primarily diesel</li> </ul>		
Design	Increased Firing Pr. And Peak Cylinder Pr.	Minimal on a g/hp-hr basis	<ul style="list-style-type: none"> <li>Typically NO<sub>x</sub> reduction by increasing PCP is due to overall engine downsizing and associated fuel consumption benefits, which translates into a g/mile NO<sub>x</sub> benefit</li> </ul>	1% - 3%	<ul style="list-style-type: none"> <li>Increased PCP's through higher compression ratio, BMEP's</li> </ul>
Waste Heat Recovery	Thermo-Chemical Recuperation	40% - 80%	<ul style="list-style-type: none"> <li>H<sub>2</sub> rich intake fuel extends lean flammability limit, thus enabling running gas engine at lower AFR's</li> </ul>	Up to 8%	<ul style="list-style-type: none"> <li>Studies have shown 4% - 8% benefit in CO<sub>2</sub> emissions with exhaust gas TCR that creates H<sub>2</sub> rich intake fuel</li> </ul>
Ignition System	Improved Ignition	Up to 70%	<ul style="list-style-type: none"> <li>Laser ignition in R&amp;D phase has shown up to 70% NO<sub>x</sub> reduction capability</li> </ul>	8% - 40%	<ul style="list-style-type: none"> <li>Laser ignition and plasma ignition have shown up to 30% to 40% efficiency improvement</li> </ul>

# SCG Supported CNG RD&D Programs for HHD Trucks



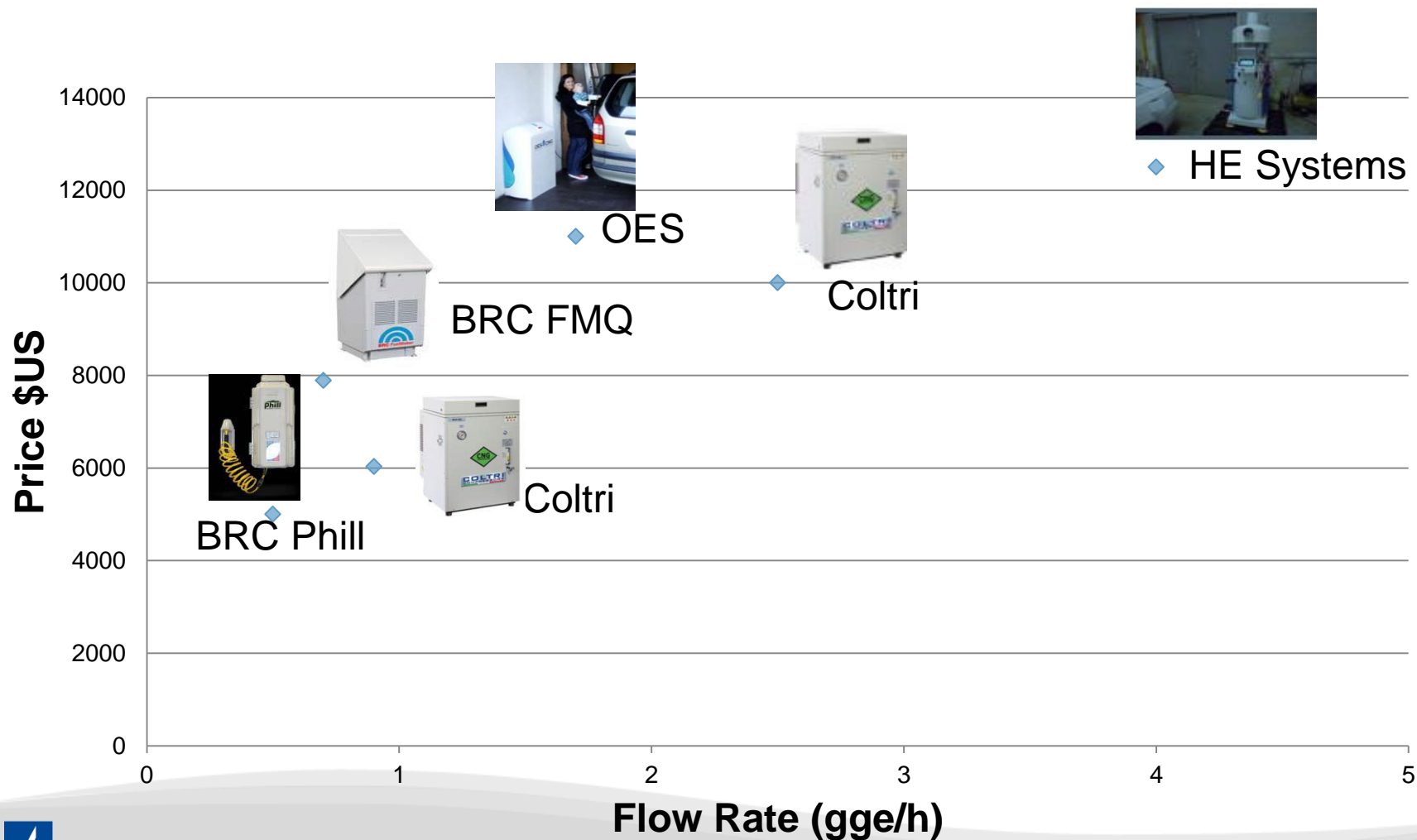
# Infrastructure - Central

- Standardized station designs
- Increased dispensing efficiencies
- Better controls, including for time-fill
- Smaller footprint
- Lower cost
- Co-Locating with Hydrogen Station
- On-site Hydrogen Production (SMR)



# Current HRA Products

## Price vs Fill Rate (GGE/hr)

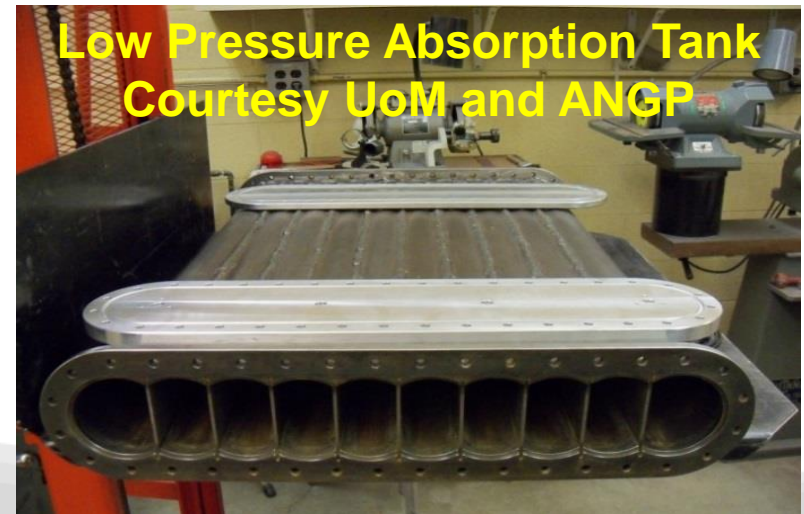


# Fuel Storage



Need:

- Lower Cost
- Lower Pressure
- Less/Conforming Space



# Light Duty CNG-Hybrid Fleet Vehicle Study

- » A review of markets and technologies suggests a commercially attractive LD CNG vehicle should target **fleet applications driving at least 50,000 miles/year**
- » The economic analysis suggests that for the high mileage fleets, an incremental retail price of around **\$3,400** could be justified relative to the current NG conversion cost on a **3 year payback, 15% fuel efficiency** improvement and **60k annual mileage**
- » Can be achieved by mix of advanced engine, tanks and mild hybrid technologies to achieve a required 15% fuel efficiency improvement using the following strategy:
  - **Mild hybridization** ideally with a 48V system and optionally electric supercharging
  - **Improved engine systems** (air supply, fuel system, etc.), limited by manufacturing implications for high volume gasoline engine production
  - An **improved NG storage** system package to limit cargo space intrusion with either a multi-cylinder underfloor installation or one of the conformable storage technologies currently under development
- » Final demonstrator technology selection will depend on:
  - Demonstrator **team partners** and their objectives
  - Target fleet **application**

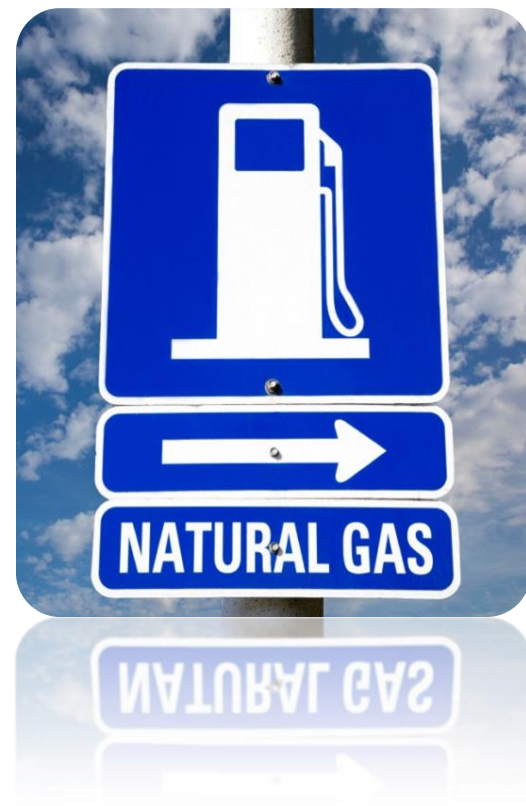
• Source: Ricardo

# Targets for the CNG-Hybrid are summarized

Category	Target
Vehicle Class	Large sedan
Target fleet application	Taxi and Police fleets Make sufficiently attractive to appeal to retail consumers
NGV type	Dedicated (or CNG dominant range extender bi-fuel)
Fuel efficiency	15% improved over current NGV technology
Performance	Similar to or better than today's NGV
Emissions class	LEV III, SULEV 30 –if needed to meet manufacturers fleet average, no direct benefit for an NGV) Consider defining path to meet 2021 PM requirement
ZEV category	Up to 2017MY –PZEV / AT PZEV
NG range	Min. 200 miles
Storage	Minimal passenger and cargo space reduction (target max 25% cargo space reduction)
HOV access	Desirable (dedicated NGV only)
Retail price target for up-fit/ conversion	Up to \$3,400* over current CNG conversion cost

# SoCalGas: Facilitating Cleaner Energy Options for our Customers

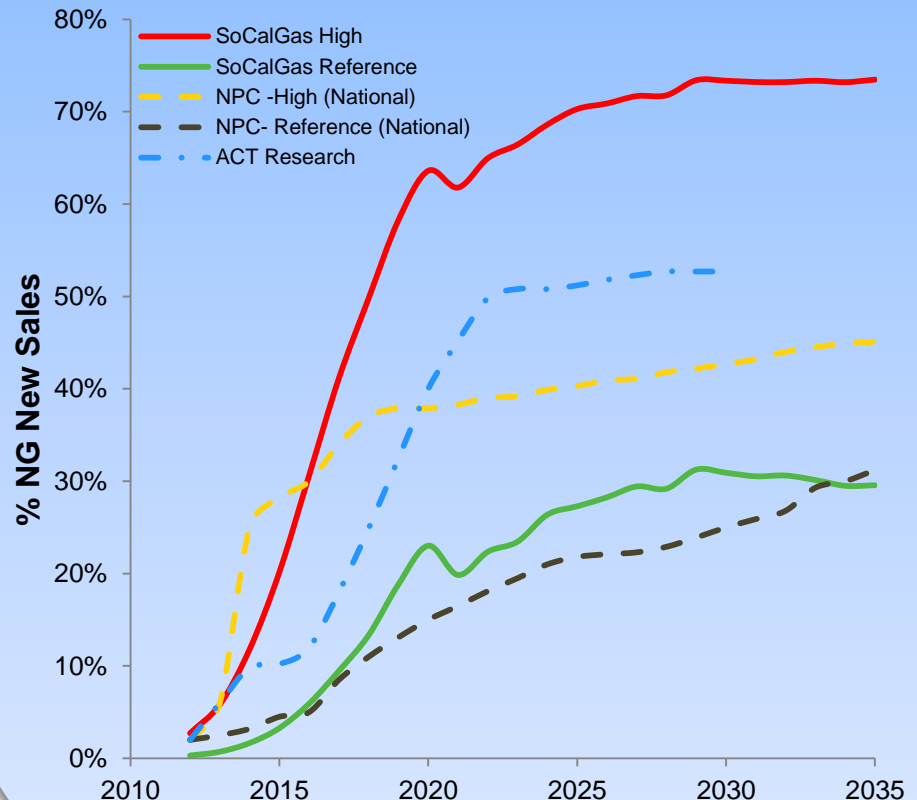
- » Offering **Compression Services** to facilitate development of NGV market.
- » Offering **Biogas Conditioning Services** to facilitate development of renewable natural gas market.
- » Evaluating **CHP Services** tariff to facilitate more efficient use of heat and power.
- » In the future, considering **LNG and/or Hydrogen Production Services** as energy economy moves to cleaner fuels.



# Economic Analysis via the “NPC Model”

- » **Economically Derived Analyses** are required to project NGV new sales (penetration rate) based on competition with diesel technology
- » **National Petroleum Council Future of Transportation Fuels Economic Decision Model (“NPC Model”)** was used to determine rates of NGV adoption by the open market
- » **NPC Model Projections** are consistent with projections published by independent research organizations
- » **SoCalGas Adjustments** are made to the NPC Model settings specific to the South Coast Air Basin marketplace
- » **SoCalGas “Reference” and “High”** NGV adoption curves via the NPC model are derived to bound the analysis

**South Coast Air Basin NG Penetration Analysis  
Heavy Heavy-duty Truck Tractor NG Sales**



# Economic Analysis via the “NPC Model”

- » **Fuel Price Projections** are based on 150% of EIA 2010 projections
- » **Model variables** adjusted for SoCalGas scenarios include *natural gas vehicle cost* and the *natural gas adoption curve* (2 settings, aggressive, conservative)
- » **SoCalGas Reference Penetration Rate** case (“SoCalGas Reference”) assumes: (1) a high price differential between NGV and Diesel Trucks; and (2) uses the conservative NGV adoption curve
- » **SoCalGas High Penetration Rate** case (“SoCalGas High”) assumes: (1) a low price differential between NGV and Diesel Trucks; and (2) uses aggressive NGV adoption curve

## SoCalGas NPC modeled cases, NG truck pricing assumptions.

Truck Group	2023 Base Diesel Vehicle Cost	NG Incremental Price in 2023	
		SoCalGas Reference	SoCalGas High
Class 7/8 Combination	\$144,953	\$47,355	\$30,028
Class 7/8 Single	\$ 190,399	\$18,906	\$7,463
Drayage	\$144,953	\$34,604	\$18,399
Refuse	\$190,399	\$18,906	\$7,463
Class 3-6	\$61,529	\$21,165	\$15,682

# Summary

- » Natural Gas is not a “Bridge” Fuel, but a Foundation Fuel
- » Engine technology advancements can achieve significant NOx and GHG Emissions Reductions to reach near zero emissions
- » Pure economics of transportation fuel will drive natural gas technology adoption by the heavy-duty trucking sector
- » Financial incentives can accelerate and increase the adoption of conventional natural gas technologies
- » New storage technologies will have tremendous impact on CNG
- » Cost effective Home Refueling Appliances is needed to encourage wide spread usage of LD vehicles